The HI and Ionized Gas Disk of the Seyfert Galaxy NGC 1144 = Arp 118: A Violently Interacting Galaxy with Peculiar Kinematics

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ABSTRACT

We present observations of the distribution and kinematics of neutral and ionized gas in NGC 1144, a galaxy that forms part of the Arp 118 system. Ionized gas is present over a huge spread in velocity (1100 km s^{-1}) in the disk of NGC 1144, but HI emission is detected over only $^1/_3$ of this velocity range, in an area that corresponds to the NW half of the disk. In the nuclear region of NGC 1144, a jump in velocity in the ionized gas component of 600 km s^{-1} is observed. Faint, narrow HI absorption lines are also detected against radio sources in the SE part of the disk of NGC 1144, which includes regions of massive star formation and a Seyfert nucleus. The peculiar HI distribution, which is concentrated in the NW disk, seems to be the inverse of the molecular distribution which is concentrated in the SE disk. Although this may partly be the result of the destruction of HI clouds in the SE disk, there is circumstantial evidence that the entire HI emission spectrum of NGC 1144 is affected by a deep nuclear absorption line covering a range of 600 km s^{-1}, and is likely blueshifted with respect to the nucleus. In this picture, a high column-density HI stream is associated with the nuclear ionized gas velocity discontinuity, and the absorption effectively masks any HI emission that would be present in the SE disk of NGC 1144.

Subject headings: galaxies: HI — galaxies: active — galaxies: evolution — galaxies: interactions — galaxies: ISM

1. Introduction

The Arp 118 system is comprised of a distorted disk galaxy NGC 1144 and an elliptical galaxy NGC 1143. NGC 1143 is $\sim 40''$ to the NW of NGC 1144, which corresponds to a linear separation of $\sim$20 kpc (assuming a distance of 110 Mpc to Arp 118). NGC 1144 is also classified as a Seyfert 2 galaxy (Hippelein 1989, hereafter H89). There exists a knotty "ring" or loop, that extends from NGC 1144 towards the companion in the north-west, and this is most easily seen in the Hα (+continuum) image of the galaxy pair shown in Figure 1. However, the structure of the disk of NGC 1144 is more complicated than a simple ring, containing many loops and filaments and a prominent dust-lane which runs from the SE to the NW from a point east of the nucleus. These details can be seen more clearly in the red HST image of Figure 1 (image courtesy of M. Malkan).

The inner region of the disk of NGC 1144 contains extended regions of star formation. Quite apart from the strong Hα emission from these regions (H89), Joy & Ghigo (1988) showed that a giant H II region complex NW of the nucleus contributed 35% of the galaxy's substantial $\lambda 10\mu$m emission. They estimated that NGC 1144 has a bolometric luminosity of 2.5×10^{11} L$_\odot$, 80% of which is re-radiated in the thermal infrared. Their 6 and 20 cm radio continuum images revealed several radio sources corresponding with blue optical emission knots, suggesting that the radio continuum was originating from recent star formation. Higher sensitivity VLA radio observations by Condon et al. (1990) supported the idea that, in addition to the Seyfert nucleus, there are other regions of bright radio emission within the inner disk, including a strong source to the east, and a spiral-like arc of emission extending over several kiloparsecs.

The early pioneering mapping of the Hα velocity field of NGC 1144 showed a huge velocity spread across the galaxy of over $\sim$1100 km s^{-1}, implying the necessity for a mass for the galaxy in excess of 10^{12} M$_\odot$ (H89). Furthermore, the velocity-field is highly asymmetric, with a change in velocity of over 700 km s^{-1} from the center of NGC 1144 to the south-eastern edge, but only a change of over 400 km s^{-1} from the center to the north-western edge of the disk. The very large spread in velocity seen in the ionized gas is also apparent in the molecular CO emission (Gao, Solomon, Downes, & Radford 1997, hereafter GSDR), where CO linewidths of 1100 km s^{-1} are seen in their IRAM single-dish (22$''$ beam) spectra. These authors showed Arp 118 to have a CO luminosity nearly twice that of Arp 220. The CO emission is distributed non-uniformly, and is highly concentrated in the SE quadrant of the ring, with much weaker emission from the NW quadrant. CO maps made with the IRAM interferometer ($5\farcs3 \times 2\farcs5$ beam) revealed that the CO emission is not centrally concentrated in the nucleus, but traces the southern arm of an inner ring coincident with the most luminous H II regions.

Hippelein (1989) suggested a dynamical model for a ring-making collision between NGC 1144 and NGC 1143 in which the disk of NGC 1144 is severely distorted by the collision. However, in order to reproduce the large spread in velocity, the mass of NGC 1144 seemed excessive (of the order of 10^{12} M$_\odot$). More recently, Lamb, Heran & Gao (1998) have attempted to model the interaction in a more sophisticated manner, including a massive halo, full self-gravity and the inclusion of gas-dynamics. Although their final model, with a total mass (including massive halo) for NGC 1144 of 5×10^{11} M$_\odot$ does produce a large velocity spread (of about 950 km s^{-1}) in the disk after the collision, it fails to reproduce the asymmetry in the velocity field of the disk, discussed earlier.

This paper presents VLA HI observations of Arp 118 in an attempt to shed new light on the interpretation of the dynamics, as well as presenting new Hα observations, revealing the kinematics of the ionized gas in the disk of NGC 1144, using the ANU 2.3-m telescope. We assume throughout this paper a distance to Arp 118 of 110 Mpc, based on an assumed heliocentric velocity[3] for the galaxy of 8800 km s^{-1}, and a Hubble constant of 80 km s^{-1}.

2. The Observations

2.1. The HI Observations of Arp 118

Arp 118 was observed at the VLA on 17 March 1996 using all 27 telescopes configured in the C-array. The correlator was set in a two IF (intermediate frequency) mode (2AD) with on-line Hanning smoothing and 32 channels per IF. For each IF we used a bandwidth of 6.25 MHz, which provided a frequency separation of 195.3 kHz per channel. This frequency separation corresponds to a velocity separation of 43.8 km s^{-1} channel^{-1} in the rest frame of the galaxy (using the optical definition of redshift). Arp 118 contains H II regions (in the ring) that have radial velocities spanning a range of more than 1000 km s^{-1} (H89). GSDR reported a wide velocity range in CO emission (1100 km s^{-1}). In order to achieve velocity coverage consistent with these observed velocity ranges, IF1 was centered at 8269 km s^{-1} and IF2 at 9230 km s^{-1}. The resulting velocity coverage of our observations was 2275 km s^{-1}. A total of 3 hours and 47 minutes were spent on source. Strong winds during the observations were responsible for a loss of 25% of our original allocation of observing time. Flux and phase calibration were performed using the sources 3C48 and 0320+053 (B1950), respectively.

The data were first amplitude and phase calibrated, and bad data due to interference were flagged and ignored by the AIPS software. An image cube was created from the UV data by giving giving more weight to those baselines that sampled the UV plane more

[3]This value of the assumed radial velocity is based on an interpretation of Hα isovelocity map presented in this paper. As we shall see, emission lines across the nucleus reveal a sudden jump in velocity which is probably related to a peculiar outflow–see text.

frequently (natural weighting). This provided a synthesized beam with a FWHM of $21''.2 \times 17''.0$.

Subtraction of the continuum emission in each line map was performed using a standard interpolation procedure based on five continuum maps free from line emission at the ends of the bands. The rms noise per channel was 0.36 mJy beam^{-1}. The highest dynamic range achieved in any channel map was 10:1. A single image cube (we will refer to this as the combined cube) was made by combining IF1 and IF2.

We determined the HI line integral profiles, or moments, from the spectral data cube. The zeroth moment corresponds to the integrated intensity over velocity and the first moment to the intensity weighted velocity (the second moment–the velocity dispersion map–was uninteresting and was not included here). We employed the following procedure. We smoothed the combined cube with a beam twice that of the synthesized beam. As a result, a smooth cube was created with a resolution of $42''.4 \times 34''.0$. We applied a signal-to-noise threshold to the smoothed cube, blanking all pixels that fell below a 3σ cutoff. A new image cube was then created by applying the blanked, smoothed cube as a "mask" to the original full resolution map. The total HI surface density map was then produced from the full resolution, blanked cube. The first-moment (intensity-weighted mean velocity field) was created from the same blanked cube. For those channels where obvious absorption was present, we employed a different procedure. In those cases, we directly fitted to the channel maps showing clear absorption using the AIPS routine IMFIT. The depth of the absorption was then determined from the fit.

2.2. Optical Spectroscopy

Observations of Arp 118 were made in 1992 with the Double Beam Spectrograph on the 2.3-m ANU telescope at Siding Spring Observatory. Longslit spectra of length 400″ were obtained at a series of position angles across the disk of NGC 1144. The dispersion was 25 km s^{-1} $pixel^{-1}$ and the slit width was 1.″8, which projects to 2 pixels at the detector. The positioning of the slits will be discussed in a later section. A full discussion of the spectral reduction and a more complete discussion of these optical data will be discussed in a separate paper. In the present paper, we will restrict our discussion to the presentation of the average velocity field of the Hα emission and its ramifications for the interpretation of the HI observations.

3. Integrated Properties of the HI, its Distribution and the Relationship Between the HI and CO Emission

Figure 2 shows the global HI profile of Arp 118, obtained by integrating the HI emission spatially over the galaxy at each velocity. Notice the narrow spread in velocity of the emission, spanning $\sim$350 km s^{-1}, compared with the huge velocity spread seen in the ionized and molecular gas. With the exception of a faint feature seen at 9200 km s^{-1}, the global HI profile has about one-third the velocity spread of the CO and Hα emission, as shown in Figure 3. A majority of the CO emission is at high velocities (in the SE) whereas the HI emission is observed at low velocities (in the NW). Taken together, the total spread in velocity seen in the HI and CO (from 8180-9290 km s^{-1}) agrees closely with the spread seen in the ionized gas (H89, also this paper).

Two faint but narrow HI absorption features may be present at velocities centered around 8800 and 9000 km s^{-1}. The lower-velocity line is close to the noise-level of the observations, but the second is stronger and is seen at the 3-5σ level over three channels (see also discussion in §4). Both lines, if real, appear spatially as negative contours against the brightest part of the radio continuum source seen in the galaxy (see §4 and 6.2). There is also fainter emission seen in the higher velocity channels near 9200-9300 km s^{-1} (see §4). We will discuss these absorption lines and the possibility that much of the HI profile from NGC 1144 is nullified by a stronger, and broader, absorption line in §6.

Integrated HI properties for NGC 1144 are given in Table 1. Table 1 also includes the integrated HI properties for a dwarf galaxy KUG 0253-003, located $\sim$8$'$ NE of Arp 118 (which we discuss fully in §7). The total HI mass was determined from the spectrum of Figure 2 from the formula:

$$\mathrm{M_H} = 2.356 \times 10^5\ \mathrm{D^2F_H} \quad (\mathrm{M_\odot}), \tag{1}$$

where D is the distance in Mpc, and

$$\mathrm{F_H} = \int \mathrm{S_\nu\ dV} \qquad (\mathrm{Jy\ km\ s^{-1}}). \tag{2}$$

Two independent single-dish profiles for NGC 1144 are available from the literature. The integrated flux density F_H detected by Bushouse (1987) using the NRAO 91-m telescope was 2.83 Jy km s^{-1} and by Jeske (1986) using Arecibo was 2.55 Jy km s^{-1}. Our value was determined to be 2.40 Jy km s^{-1}, or 85% of the total emission quoted by Bushouse and 94% of the total emission quoted by Jeske. The lower value obtained here is consistent with the possibility that the C-array has resolved-out faint extended HI emission which would be detected by the single-dish observations. However, neither single dish spectra cover the velocity range of the possible absorption lines, and our estimate of the total HI mass given in Table 1 does not take into account the possible contamination of the

HI emission line profile by a broad, but deep, HI absorption feature.

The total HI mass of Arp 118 based on our C-array observations is $M_H = 7.0 \times 10^9$ $M_\odot$. This compares with an estimated molecular mass of 1.8×10^{10} $M_\odot$ (GSDR), based on the standard galactic H_2 mass-to-CO luminosity. GSDR, however, noted that the standard conversion factor might be 2-3 times lower in Arp 118 than in the Milky Way, which would therefore correspond to a molecular hydrogen mass of $\sim$6-9 $\times$ 10^9 $M_\odot$.

We also include in Table 1 an estimate of the dynamical mass M_d (see for example Appleton, Charmandaris, & Struck 1996) of NGC 1144. The value of M_d was calculated using the formula:

$$M_d = \frac{[(1/2)\Delta V_{1/2} \mathrm{cosec(i)}]^2 \, R_{HI}}{G} \qquad (M_\odot) \tag{3}$$

where R_{HI} is the radius of the HI disk, $\Delta V_{1/2}$ is the width of the profile where the flux density is one-half the peak, and i is the inclination of the disk. This formula applies to gas that is in bound circular orbits. Note that the assumption of circular orbits and a "normal" rotation curve may be quite incorrect in Arp 118. Because the spread in velocities of the HI emission is about one-third that of the CO (and Hα), we have estimated $\Delta V_{1/2}$ from the combined HI and CO profiles, giving a $\Delta V_{1/2}^{CO+HI}$ of 1020 km s^{-1}. Based on the HI map, we estimate R_{HI} to be 10 kpc, and i = 50°, based on the ratio of the major to minor axis of the optical outer ring. Hence we obtained a value of $M_d = 1 \times 10^{12}$ $M_\odot$.

Figure 4 contains the integrated HI distribution of Arp 118, overlayed with a digitized sky survey (DSS) grey-scale image of Arp 118. The HI emission is distributed non-uniformly throughout the disk of NGC 1144, and is concentrated in the NW quadrant of the ring, with fainter emission to the south.

Figure 5 (see also Figure 6) is an overlay of the integrated HI map with the a grey-scale image of the CO knots imaged by GSDR. As mentioned, the high resolution CO data of GSDR shows that the CO emission traces the southern arm of the radial ring wave (the approximate location of the ring has been drawn to guide the eye). Further, the knots of CO emission are coincident with luminous H II regions, also concentrated along the southern arm of the ring. Inspection of Figure 5 reveals that the brightest complexes of CO emission do not overlap the HI emission. In Figure 6 we have convolved the CO emission to the same beam size as our VLA data. The CO emission appears to, more strikingly, "fill-in" the "missing" HI emission in the south-eastern half of NGC 1144. Considering Figures 3, 5, and 6, the HI and CO appear "segregated", both spatially and kinematically. Note, however, that we use the word "segregated" rather loosely, since there is weaker CO emission in the NW quadrant (see next paragraph), and low-level HI emission in the SE. The word is used to point to the fact that the distributions of CO and HI are asymmetrically peaked, CO to the SE and HI to the NW.

Interestingly, there is a striking similarity between the single dish CO profile in the NW quadrant of the of the ring and our HI profile (see Figure 1 in GSDR for the single dish profile). The CO profile peaks at a velocity of 8250 km s^{-1} and the HI profile peaks at 8267 km s^{-1}. Both profiles fall off rapidly towards higher velocities.

4. HI Kinematics

In Figure 7 we present those channel maps containing detectable emission from 8180 to 8661 km s^{-1}. At the rest frame of the galaxy, the channel separation is 43.8 km s^{-1}. The emission at the lower velocity channels is mainly concentrated in the northern part of the galaxy in the region associated with the NW quadrant of the outer optical ring seen in Figure 1, but also extends significantly to the NE, outside the optical bounds of the galaxy (V = 8267 km s^{-1}). The emission becomes more scattered and moves further south as one proceeds to higher velocities. There is a marginal detection of faint emission to the SE of the main body of the galaxy around 8573 km s^{-1} and 8661 km s^{-1}. With the exception of a faint HI features centered on the nucleus at velocities of 9200 to 9300 km s^{-1} (see later), no significant HI emission is observed at velocities in excess of 8661 km s^{-1}.

Figure 8 contains the mean velocity field of Arp 118, which appears rather disturbed as compared with the optical velocity (see below). The velocities appear, approximately, to run from lower velocities in the north to higher velocities in the south. Except for contours at 8355 km s^{-1} , there is little emission from the SE disk of NGC 1144. The velocity isocontours generally have a bent and/or rather distorted S-shaped appearance. In the regions of common coverage between the optical and HI velocity fields (see later), there is approximate agreement. However, the fact that much of the HI disk of NGC 1144 is missing in the SE make the HI velocity field very difficult to interpret.

Figure 9 contains another set of channel maps showing the faint absorption features seen against the nuclear radio disk. The absorption appears in 5 channels, at the same spatial location, but is strongest at a velocity of 9011 km s^{-1}. Figure 9 also contains a faint emission feature seen near the nuclear region. This emission appears in 5 channels, most strongly in in the 9318 and 9274 km s^{-1} channels.

In order to show the absorption features more clearly, we have constructed, in Figure 10, a spectrum through the unblanked data cube centered on the galaxy's nucleus. This has the effect of integrating *only* that emission or absorption associated with the nuclear source. This spectrum differs in nature from the integrated (global) spectrum of Figure 2 because it concentrates on the nuclear regions only, and is determined from the cube without any flux-threshold blanking. Figure 10 reveals faint nuclear absorption and emission. Interestingly, Figure 10 suggests that the two faint absorption features, which we isolated in Figure 2, may be part of a faint, broader absorption complex. The absorption features at their deepest are detected at the 4σ (8791 km s^{-1}) and 5σ (9011 km s^{-1}) level. Figure 10 also contains the faint emission features at velocities of 9200 to 9300 km s^{-1}, as shown in Figure 2. These emission features are at a similar level of significance as the absorption features. In §6.2 we will return to the astrophysical implications of the broad absorption features and their possible effect on the total HI profile.

5. The Kinematics of the Ionized Disk

In Figure 11, we show the mean velocity field of the Hα emitting gas based on the observations made with the ANU 2.3-m telescope. A more complete discussion of these optical data will be presented in a separate article (McCain and Freeman, in preparation). In this paper we restrict ourselves to a discussion of the velocity field of the galaxy. In the upper right of Figure 11 we show the coverage of the long-slits used to create the velocity map. The slits ranged in position angle from 318° to 273°, and each slit was positioned on the nucleus of the elliptical companion NGC 1143 during each observation. The one exception was a slit oriented at 309° which was positioned to pass through the nucleus of NGC 1144, but was not centered on NGC 1143. Ionized gas emission was detected over the entire face of NGC 1144. The velocity field in the upper left of Figure 11 shows the entire Hα emitting disk, and the inset to the lower right shows the details of the disk closer to the center. We overlay the contour map of the velocity field with a grey-scale representation of the λ20cm radio continuum emission from Condon et al. (1990), and we will discuss the significance of this later.

The velocity field of NGC 1144, derived from the ANU 2.3-m spectra, is very similar in overall appearance to the earlier work of H89. The gross characteristics of the system are large-scale rotation over a velocity range of 1100 km s^{-1}. The ANU 2.3-m data show a sudden velocity discontinuity in the vicinity of the nucleus, which in the inset shows a drop in radial velocity of about 600 km s^{-1}, from a value in the disk of around 9000 km s^{-1} to a value around 8400 km s^{-1}. This region is almost unresolved at the level of the seeing ($1''$), and so the velocity discontinuity is most probably associated with the nucleus. The cross shows the nominal position of the optical nucleus, but this is not well determined from the spectra. (Note: we have assumed in overlaying the map with the radio image that the velocity discontinuity corresponds to the position of the nuclear source).

Putting aside for the moment the question of the origin of the velocity jump at the center of the galaxy, we now address the question of the value of the systemic velocity of the galaxy. Based on the appearance of the isovelocity contours, it would be normal to consider the systemic velocity of a galaxy to be the velocity associated with the contour which passed through the nucleus. Ignoring the velocity discontinuity, the most natural contour which would pass close to the nucleus, and which runs parallel to the minor axis of the galaxy, would be the velocity contour at 9050$\pm$50 km s^{-1}. It is interesting to note that the ANU 2.3-m spectra show CaII H and K absorption lines, presumably from the underlying stellar population in the galaxy, which yield a velocity of 9000$\pm$100km s^{-1} for the nucleus, in approximate agreement with the global velocity field of the ionized gas. It is clear that the velocity discontinuity is a major deviation away from this value for the systemic velocity, since the emission lines in the nucleus yield a velocity of 8400km s^{-1}. Does this mean that the nucleus is moving relative to the gas disk, or simply that there are peculiar motions in the ionized gas in and around the core? In the next section, we argue for the latter, based on the HI absorption results.

6. What is the Origin of the Asymmetric HI Distribution in NGC 1144?

One of the surprising results of our HI observations of NGC 1144 is the rather dramatic asymmetry in the distribution of the gas in the disk. Our VLA observations show that most of the gas detected is centered on the NW half of the galaxy, whereas ionized and molecular gas are spread over the whole disk, but are concentrated mainly in the southeastern half of the galaxy. This apparent segregation is also reflected in the kinematics. HI from the disk of NGC 1144 is seen exclusively at velocities below 8600 km s^{-1}, and little detectable HI emission is seen over a wide range of velocities represented by a large part of the ionized and molecular disk. We address below two possible explanations for the missing HI. The first is the possibility that the segregation is a result of the large-scale conversion of HI into molecules via strong shocks in the disk of this violently colliding galaxy. The second, and perhaps more plausible explanation, is that HI is present over the entire velocity range, but that very powerful, and extremely broad HI absorption lines are present in the nuclear regions that have "nullified" the entire emission-line profile of the galaxy over a 600 km s^{-1} interval. The evidence for the latter is strengthened by the discovery of a rapid change in velocity in the ionized gas over the same velocity range in the nucleus, as we discussed in the previous section.

6.1. Conversion of atomic to molecular gas?

If we take at face-value the asymmetry in the HI distribution in the disk of NGC 1144, we can attempt to determine quantitatively the relative importance of the atomic and molecular hydrogen content across the disk NGC 1144 by calculating the molecular-to-atomic gas mass ratio, M_{H_2}/M_{HI}, in the NW and SE regions. We have converted the observed CO emission from GSDR into a mass of molecular gas (using the standard galactic conversion from CO to H_2), and calculated the HI mass, separately, for the NW and SE regions. The molecular-to-atomic gas mass ratio is 0.77 in the NW section of the ring, consistent with the observed ratios in normal spiral galaxies (Casoli et al. 1998). The ratio is very large in the SE section, 17.6, consistent with ratios measured in other interacting, infrared luminous galaxies (Mirabel & Sanders 1989). If this scenario is correct, the gas mass ratios suggest that the dominant state of the interstellar medium proceeds from mainly atomic in the NW, to molecular in the SE. In the SE region less than 6% of the interstellar gas is in atomic form. Considering that the total (HI+H_2) mass of hydrogen remains approximately equal in both regions (∼1 and 2 $\times$ 10^{10} $M_\odot$ in the NW and SE, respectively) suggests the possibility that there may be a large scale conversion of HI to H_2 in the southern region of NGC 1144.

One possible way to enhance the molecular gas mass fraction is by compressing the disk in NGC 1144. Modest compression and/or shocks in the interstellar medium can lead to the conversion of atomic to molecular gas (Elmegreen 1993; Honma, Sofue, Arimoto 1995). The salient features of Elmegreen's model are that the HI-H_2 gas phase transition depends sensitively on the pressure in the interstellar medium and the radiation field: H_2 molecules are formed on the surface of dust, but can be destroyed by UV photons. The results of his models imply that large regions within galaxies can spontaneously convert atomic into molecular gas following an interaction, a tidal encounter that has led to accretion, or increase in the gas surface density.

While it is plausible that such a process is occurring in the disk of NGC 1144, there exists a much more likely explanation for the "missing" HI, namely the possibility of HI absorption.

6.2. HI absorption

We will begin this section by discussing the HI absorption line seen at approximately 9000 km s^{-1} in the channel maps, as shown in Figure 9. Figure 12 contains a contour map of the continuum emission, overlayed upon a grey scale representation of the integrated

HI emission. The absorption appears nearly coincident with the peak continuum emission in NGC 1144. The total flux we detected from the continuum source associated with NGC 1144 was 139.5 mJy, within a synthesized beam of $21''.2 \times 17''.0$, which is in excellent agreement with the 20 cm flux of 136 mJy from Condon et al. (1990) in an $18'' \times 18''$ beam. However, higher resolution observations of the continuum emission by Condon et al. reveal a compact nucleus, and two extra-nuclear emission regions, as well as a faint arc within the inner disk (see greyscale overlay in upper right of Figure 11). In determining the HI column density responsible for the faint absorption line at 9000 km s^{-1} it is necessary to assume a plausible location for the HI absorbers, i.e., which of the continuum emitting regions, seen in the higher resolution continuum image, the absorbers cover.

For an HI cloud seen in absorption (F_{abs}) against a continuum source (F_{con}), the optical depth, τ, of the cloud is given by (e.g. Mirabel 1982):

$$\tau \quad = \quad \ln(1 \;+\; \frac{F_{abs}}{F_{con}}) \tag{4}$$

and hence the hydrogen column density N_{HI} is given by:

$$N_{HI} = 1.823 \times 10^{20} \int \; T_{S100} \; \tau \; dv \quad \text{atoms cm}^{-2} \tag{5}$$

where T_{S100} is the spin temperature in units of 100 K.

As a working hypothesis, we will assume that the HI seen in absorption lies in the disk of NGC 1144, and exhibits similar kinematics to the ionized gas. It can be seen from the 20 cm map of Condon et al. (Figure 11) that the brightest radio emission regions are the unresolved nucleus (25.9 mJy) and the eastern extra-nuclear region (22.9 mJy: angular size $2'' \times 1''$). The third extra-nuclear region to the west of the nucleus is significantly fainter (9.4 mJy), and probably does not contribute to any absorption profile. Of the strong emission regions, only the eastern radio source lies in projection against the velocity field at 9000 km s^{-1}. We will adopt this source as a plausible continuum feature against which we might see the higher velocity HI absorption feature of Figure 2.[4] For an absorption feature seen over one channel (43.8 km s^{-1}) and a depth F_{abs} = 2 mJy, and F_{con} = 22.9 mJy, the neutral hydrogen column density needed to create the absorption will be $N_{HI} = 6.7 \times 10^{20}$ T_{S100} atoms cm^{-2} $channel^{-1}$. Since the feature is seen over three channels, the total column density is similar to that seen commonly in the disks of galaxies in emission, and is $\sim$2 $\times$ 10^{21} T_{S100} atoms cm^{-2}. A single cloud covering the area of the eastern radio emitting region, and with the above column density, would have a mass of $\sim$8 $\times$ 10^6 $M_\odot$, the mass of a typical giant molecular cloud (GMC). Hence our basic hypothesis that the absorbing cloud lies in the disk of NGC 1144 is consistent with the observations.

The next question to ask is why we don't see a large population of such clouds in emission, as we apparently do in the NW part of the disk?[5] Here we are confronted with two possible alternatives. The first hypothesis - which we call the "minimal absorption" hypothesis - is that the clouds we see in absorption have a small filling factor compared with the larger VLA beam ($21'' \times 17''$). How many such clouds could be hidden within the C-array VLA beam before we would see the clouds in emission rather than absorption? The 3σ noise per channel was found to be approximately 1 mJy $beam^{-1}$, and so it would be possible to hide 1.3 $\times$ 10^8 $M_\odot$ of HI within one beam and still fail to detect it. If we assume that such emission would be in the form of the clouds we detect in absorption, this implies an upper limit of 16 absorber clouds per beam that could go undetected in emission. As a

[4]Had we chosen the nuclear source, rather than the eastern extra-nuclear source, the calculated optical depth would be similar since its flux is almost identical

[5]We remind the reader that we do see some faint emission centered on the nucleus over a few channels in the velocity range 9200-9300 km s^{-1}.

point of reference, in the NW disk of NGC 1144, the typical column density of gas seen in emission would imply approximately 200 similar clouds per beam. This would argue for a depletion in the total HI mass in that region of the disk, and would be consistent with the scenario presented in §6.1, in which some process is destroying HI clouds in the SE part of the disk of NGC 1144.

A second hypothesis - we call the ”extreme-absorption” hypothesis - is that the entire HI profile from 8400 to 9000 km s^{-1} is affected by *deep absorption* against the nucleus, which nullifies any *emission* seen in the larger VLA C-array HI beam. We note that the HI emission and absorption in the nucleus is spotty and not “perfectly” balanced. Such a scenario is strongly hinted at in Figure 10, which shows the possibility of a broad absorption complex in the nuclear region.

Strong, broad (up to 700 km s^{-1} wide) HI absorption against Seyfert nuclei is not uncommon (e.g. Dickey 1982,1986; Mirabel 1982,1983). Van Gorkom et al. (1989) detected HI in absorption (up to $\sim$600 km s^{-1} wide) against the nuclei of radio elliptical galaxies. These systems have absorption features which are consistent with both infalling and outflowing HI gas. Further, IC 5063 has a 700 km s^{-1} HI absorption feature, with a depth of 10-15 mJy, seen against its Seyfert 2 nucleus (Morganti, Oosterloo, & Tsvetanov 1998). The absorption is seen blueward of the systemic velocity of IC 5063, indicating a blueshifted outflow of HI. The interpretation of these various observations is that the HI is likely to be in the form of an inflowing/outflowing stream, or complex of clouds, seen in projection against a background continuum source (the AGN). If a high column-density stream of HI were mixed, for example, with the ionized gas associated with the velocity discontinuity seen in the nucleus (Figure 11), then such absorption would have a profound effect on the HI emission spectrum.

To explore the feasibility of the extreme-absorption hypothesis, we will assume that, in the absence of absorption, NGC 1144 would have a normal double-horned HI profile with a velocity width similar to the observed spread in the ionized gas velocities (1100 km s^{-1}) and a single-channel flux of 10 mJy over that mid-range of the spectrum. We can then ask what column density of HI would be required to be seen throughout the range of 8400-9000 km s^{-1} (the velocity jump seen near the nucleus in the ionized gas) to reduce the putative HI emission line profile to zero flux? If F_{abs} = 10 mJy and the continuum source is the nucleus (F_{con} = 25.9 mJy) then we derive $N_{HI} = 4.2 \times 10^{22}$ T_{S100} atoms cm^{-2} over the full 600 km s^{-1} range seen at the velocity discontinuity. This must be considered an upper limit to the true column density since the radio source is not resolved in the observations made by Condon et al. (1990). If we assume it is just resolved, the implied cloud mass of the HI absorbers would be 1.6×10^8 $M_\odot$, assuming that the area of the nuclear region is 1.65 square arcseconds, the approximate area of the beam from Condon et al. (1990).

The advantage of the extreme-absorber hypothesis over the minimal-absorber picture, is that it can readily explain the lack of HI in emission from the mid- to SE disk of NGC 1144, and indeed from the HI data-cube over the entire range of velocities in excess of 8661 km s^{-1}. It also is very testable. Higher resolution HI observations should separate any, so far only hypothetical, deep absorption in the nucleus from extended HI emission in the disk.

7. HI Distribution and Kinematics of a "Ultra-violet Excess" Dwarf Companion in the Arp 118 Group = KUG 0253-003

We have discovered HI emission from a position ($\sim 8'$ to the NE of Arp 118 = 256 kpc) corresponding to the same spatial location as a galaxy found by Takase & Miyauchi (1988) in a survey of ultraviolet-excess galaxies (KUG 0253-003 or PGC 011066). NED[6] lists this galaxy as a "spiral" with a blue magnitude of 16.5, and with major & minor axes of $0\farcm3 \times 0\farcm3$ and no cataloged redshift. There are no obvious spiral arms in the DSS image, and it appears as a high-surface brightness, compact galaxy.

Figure 13 contains the global HI profile of the companion, which is narrow and single peaked, with a $\Delta V_{1/2}$ of 51 km s^{-1}. The systemic velocity (V_{HI}) is 8749 km s^{-1}, which gives a velocity difference of $\sim$460 km s^{-1} between the distant, uv-excess dwarf companion and Arp 118. Assuming it to be part of the extended Arp 118 group, the HI mass of KUG 0253-003 is 3.4×10^9 $M_\odot$, roughly half the value of Arp 118 (see Table 1). This "dwarf" galaxy therefore appears to be somewhat rich in atomic hydrogen. In Figure 14 we present the integrated HI image of the companion, overlayed with a DSS grey-scale image. The HI emission is smooth, with a peak that appears to be somewhat off-set from the bright centrally concentrated light distribution of KUG 0253-003. The HI emission appears to be elongated to the SW (towards Arp 118).

Figure 15 contains the 3 channel maps with HI emission from the companion. Figure 16 shows the mean velocity field of KUG 0253-003, which, though we barely resolve the galaxy, hints at rotation, with a major kinematic axis that runs approximately SE to the NW.

One might speculate that the dwarf is undergoing a major episode of star formation, perhaps as a result of an interaction with Arp 118. The difference in velocity (460 km s^{-1}) and projected separation suggest a time-scale of 5×10^8 years to get to its present location

[6]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

if it did pass close to Arp 118 in the past. This is the typical crossing-time for a small group and does not seem unreasonable.

8. Conclusions

A mapping of the neutral and ionized gas in the Arp 118 system has revealed the following:

1) The HI emission, in addition to being highly disturbed, is distributed non-uniformly throughout the disk of NGC 1144, being highly concentrated in the NW region of the ring away from the nuclear star formation complexes and the Seyfert 2 nucleus. This distribution is anti-correlated with the most powerful CO emission which lies in the SE part of the disk. Ionized gas is seen distributed throughout the entire disk of NGC 1144. No HI or Hα emission is seen associated with the elliptical companion NGC 1143.

2) Unlike the huge spread in the ionized gas velocities in the disk of NGC 1144 (1100 km s^{-1}), strong HI emission is observed only over one-third of this interval and is consistent with HI emission associated with the NW part of the ionized disk. HI emission over a 600 km s^{-1} interval (which covers most of the mid-disk and SE half of the ionized disk) is missing from the velocity channels.

3) Observations of the ionized gas component of the disk of NGC 1144 show that, in addition to the large-scale rotation of the galaxy over the range of 1100 km s^{-1}, there exists a sudden jump in velocity of the ionized gas in the nuclear regions of the galaxy of approximately 600 km s^{-1}. If we adopt the systemic velocity of the Hα disk to be 9000 km s^{-1} determined from the large-scale velocity field away from the nucleus, then this implies blue-shifted gas streaming motions within the nucleus. Alternatively, the observations may imply that the nucleus itself is moving at a velocity of 600 km s^{-1} with respect to the host

disk. However, CaII H & K absorption lines support a nuclear velocity of around 9000 km s^{-1} suggesting that it is the ionized gas that has the peculiar motion in the nucleus.

4) Very weak HI absorption is seen against the radio continuum sources (including an off-center nucleus) which are concentrated in the SE section of the ring. We interpret the absorption lines in two ways: a) the "minimal-absorption" hypothesis, in which the weak absorption lines are assumed to be the only absorption present, and b) the "extreme-absorption" hypothesis, in which it is assumed that there is strong and deep nuclear HI absorption over the same velocity range as the Hα velocity discontinuity (600 km s^{-1}). Hypothesis a) results in an explanation for the missing HI in the mid-to-SE disk of NGC 1144 as a depletion of HI clouds by at least a factor of 10 over the NW disk. However, b) offers the advantage that it explains the missing HI in the disk of NGC 1144 as being due to a high column-density stream of HI seen in absorption against the nucleus, negating the HI emission in the larger-scale disk. If true, b) suggests a streaming of high column-density HI gas ($N_H > 4 \times 10^{22}$ atoms cm^{-2}) is mixed with ionized gas and is emanating from the nucleus at up to 600 km s^{-1}. The total HI mass of such a stream could be as high as 1.8×10^8 $M_\odot$ in the neutral hydrogen component alone.

5) We detect an HI-rich dwarf galaxy $8'$ to the NE of Arp 118. The dwarf galaxy, KUG 0253-003, was detected in a survey of "uv excess" galaxies, and shows a disturbed HI distribution with an extension pointing towards Arp 118. It is possible that the galaxy has interacted with the Arp 118 system in the past (500 Myr ago, based on its projected separation and velocity difference).

It is clear that high signal-to-noise HI observations of much higher spatial resolution are required to determine the true nature of the absorption spectrum of NGC 1144. The source that is naturally implicated is the nuclear source, which we know has a flux of about 25 mJy at λ20 cm. Although observations on the scale of several arcseconds will be required to determine whether the disk of NGC 1144 is truly asymmetric in its HI content, the study of the postulated high-column density stream will require sub-arcsecond observations of the absorption lines over the nuclear source. If we are correct in our extreme-absorber hypothesis, the absorption lines could be as deep as 10 mJy (against a source of 25 mJy) over a velocity range from 8400 to 9000 km s^{-1}.

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REFERENCES

Appleton, P.N., Charmandaris, V., & Struck, C. 1996, ApJ, 468, 532

Bushouse, H.A. 1987, ApJ, 320, 49

Casoli, F., Sauty, S., Gerin, M., Boselli, A., Fouque, P., Braine, J., Gavazzi, G., Lequeux, J., & Dickey, J. 1998, A&A, 331, 451

Condon, J.J., Helou, G., Sanders, D.B., & Soifer 1990, ApJS, 73, 359

Dickey, J.M. 1982, ApJ, 263, 87

Dickey, J.M. 1986, ApJ, 300, 202

Elmegreen, B.G. 1993, ApJ, 411, 170

Gao, Y., Solomon, P.M., Downes, D., & Radford, S.J.E. 1997, ApJ, 481, L35 (GSDR)

Hippelein, H.H. 1989, A&A, 216, 11 (H89)

Honma, M., Soufe, Y., & Arimoto, N. 1995, A&A, 304, 1

Jeske, N.A. 1986, PhD Thesis, University of California, Berkeley

Joy, M., & Ghigo, F.D. 1988, ApJ, 332, 179

Lamb, S.A., Hearn, N.C., & Gao, Y. 1998, ApJ, 499, L153

McCain, C. 1997, PhD Thesis, Australia National University, Canbera

Mirabel, I.F. 1982, ApJ, 260, 75

Mirabel, I.F. 1983, ApJ, 270, L35

Mirabel, I.F., & Sanders, D.B. 1989, ApJ, 340, L53

Morganti, R., Oosterloo, T., & Tsvetanov, Z. 1998, ApJ, 115, 915

Takase, B., & Miyauchi-Isobe, N. 1988, Annals of Tokyo Astronomical Observatory, 22, 41

van Gorkom, J.H., Knapp, G.R., Ekers, R.D., Ekers, D.D., Laing, R.A., & Polk, K.S. 1989, AJ, 97, 708

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Fig. 1.— Hα image (top), taken with Steward Observatory 90-inch telescope, and HST F606W image (bottom), courtesy of Matt Malkan. The Hα image courtesy of M. A. Bransford and A. P. Marston from unpublished data

Fig. 2.— Global HI profile of Arp 118. The arrows point to two absorption features. The fainter absorption feature at $\sim$8800 km s^{-1} is of marginal significance and further observations will be necessary to confirm its reality.

Fig. 3.— Global HI profile of Arp 118 (solid line) over-plotted by global profile of CO emission (dashed line, GSDR). The double headed arrow indicates the range of velocities of the H II regions around the ring (H89). Note how the HI emission peaks at low velocities, whereas the CO emission peaks at high velocities. The peaks of the HI and CO profiles were arbitrarily normalized to a value of 1.0.

Fig. 4.— Grey scale Digital Sky Survey image of Arp 118 with a contour map of the integrated HI distribution. The contour increment is 50.0 Jy beam^{-1} m s^{-1}, and the level of the lowest contour is 100 Jy beam^{-1} m s^{-1}.

Fig. 5.— Integrated HI contour map overlayed with a grey-scale image of the CO knots imaged by GSDR using the Plateau de Bure Interferometer. The CO knots were detected at a different resolution ($5''\!.3 \times 2''\!.5$ beam) than the VLA beam.

Fig. 6.— Same as Figure 6, except the CO emission is convolved to the same VLA beam shape used in the HI observations.

Fig. 7.— Contour plots of the 12 channel maps which contain detectable HI emission, overlayed with the DSS gray-scale image of Arp 118. The velocity (in km s^{-1}) is displayed in the upper right. The channel width is 43.8 km s^{-1} in the rest frame of the galaxy. The contour increment is 3.6×10^{-4} Jy beam^{-1}, and the lowest contour displayed is at 3σ.

Fig. 8.— Mean velocity field of Arp 118, with the velocity contours labeled in units of km s^{-1}. The cross denotes the location of the nucleus of NGC 1144.

Fig. 9.— A sequence of channel maps containing the faint absorption and emission features discussed in the text. The contour increment is $\pm 3.3 \times 10^{-4}$ Jy beam^{-1} and the lowest contour displayed is 3σ. The dotted grey lines denote negative contours and the solid grey lines denote emission. Note the absorption features centered on the nucleus most strongly in the 8791 and 9011 km s^{-1} channels, and the emission features centered near the nucleus in velocity range 9186 to 9318 km s^{-1}

Fig. 10.— HI profile, extracted from data cube in a 10×10 pixel box centered on the nuclear absorption feature. This profile is the integrated emission and absorption associated with the nuclear source only, and therefore differs significantly from the global profile of Figure 2.

Fig. 11.— Contour plot of the Hα velocity field of the disk of Arp 118 (upper left). In the upper right are the slit positions used for determining the Hα velocity field, and in the lower right an inset shows more detail of the kinematics of the nuclear region. Note the velocity discontinuity in the nuclear region of 600 km s^{-1}. Finally, in the upper left, we overlay a grey-scale representation of the high resolution λ20 cm image of NGC 1144 from Condon et al. (1990). In making the overlay between the 20 cm continuum image and the velocity field, we have assumed that the position of the velocity discontinuity is the nucleus.

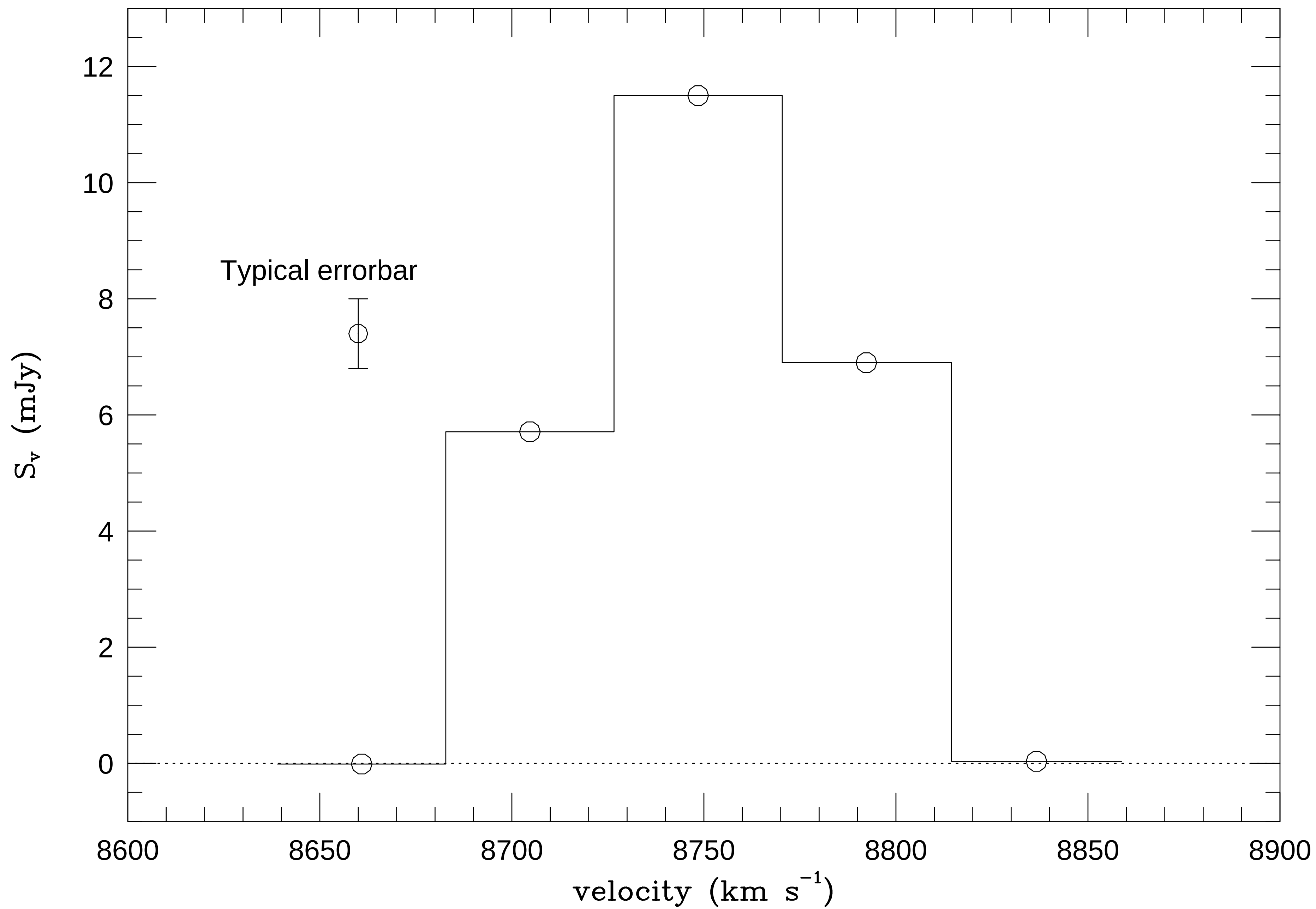
Fig. 12.— Contour plot of the continuum emission overlayed on a greyscale image of the integrated HI emission, from Arp 118. The contours are $(-2,2,4,8,16,32,64,128,256) \times 3.6 \times 10^{-4}$ Jy beam^{-1}. The grey scale flux ranges from 80 to 500 Jy beam^{-1} m s^{-1}.

Fig. 13.— Global HI profile of dwarf companion.

Fig. 14.— Grey scale DSS image of dwarf companion with a contour map of the integrated HI distribution. The contour increment is 25 Jy beam^{-1} m s^{-1}, and the level of the lowest contour is 75 Jy beam^{-1} m s^{-1}.

Fig. 15.— Channel maps containing HI emission from dwarf companion. The contour increment is 3.3×10^{-4} Jy beam^{-1} and the lowest contour displayed is 3 σ.

Fig. 16.— Mean velocity field of dwarf companion, with the velocity contours labeled in units of km s^{-1}.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8
6
4
2
0
S_ν (mJy)
8600
8650
8700
8750
8800
8850
8900
velocity (km s^-1)